TMS 2019

San Antonio, Texas

Predicting Deformation and Cracking as a Function of Additive Manufacturing Process Parameters

Cornelia Altenbuchner, Richard Otis, Andre Pate, Samad Firdosy, Peter Dillon, Andrew Shapiro (JPL)

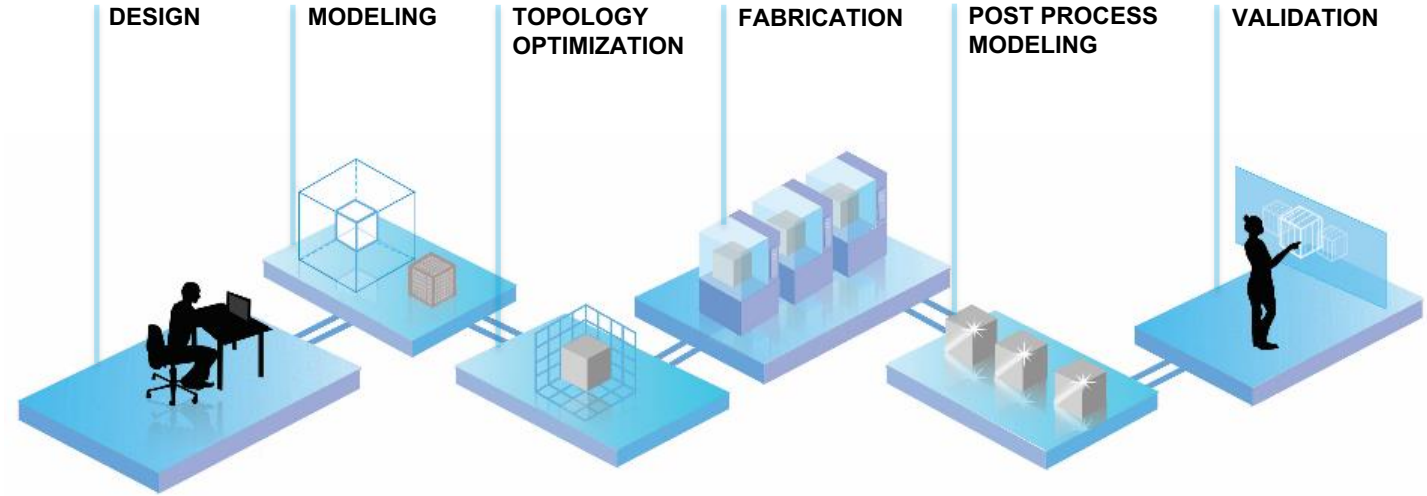
Umberto Scipioni Bertoli, Julie Schoenung (UC Irvine)

Presented by Richard Otis

March 11, 2019

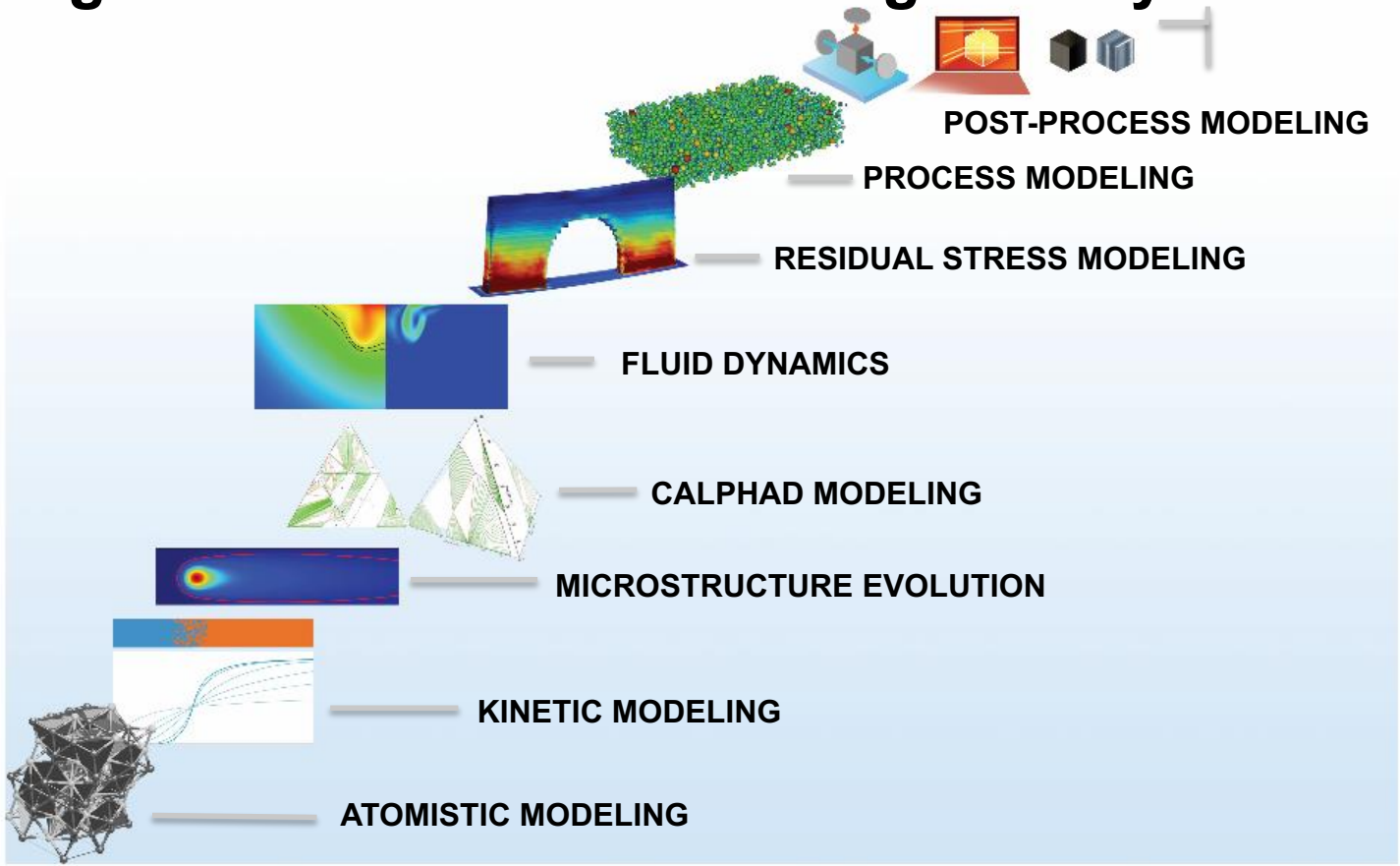
Jet Propulsion Laboratory
California Institute of Technology

Additive Manufacturing



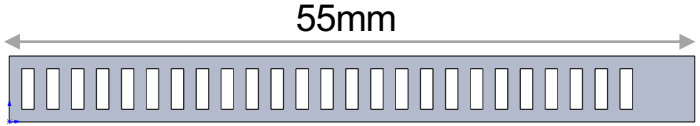
Images courtesy of NASA/JPL

Modeling for Additive Manufacturing of Alloys



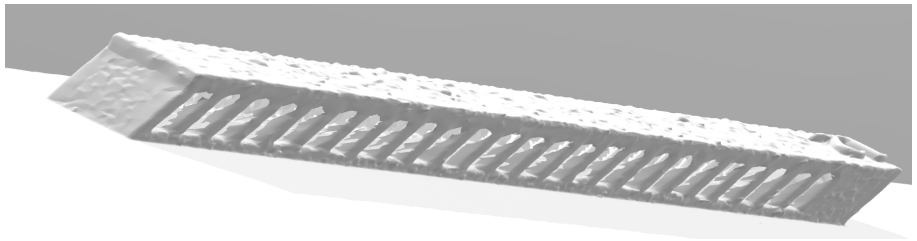
Residual Stress

- Stress induced by the manufacturing process
- Affected by
  - Thermal history
  - Phase transformations
- Can lead to deformation or failure



Residual Stress Test Sample
316L Stainless Steel

Drawing (*above*)
Structured-Light Scan (*below*)



Toward Part-Level Residual Stress Models

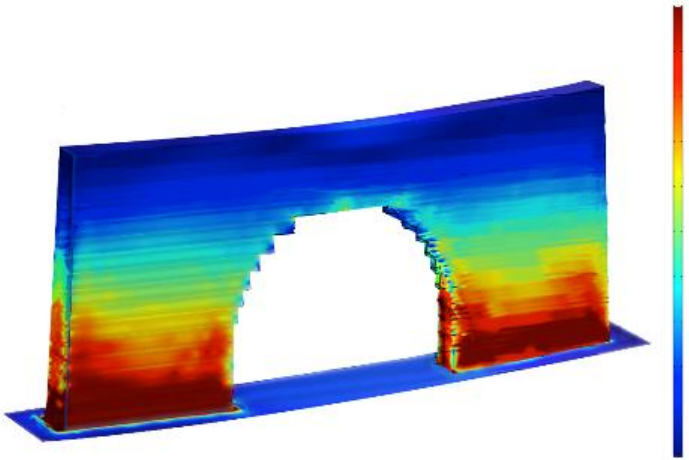
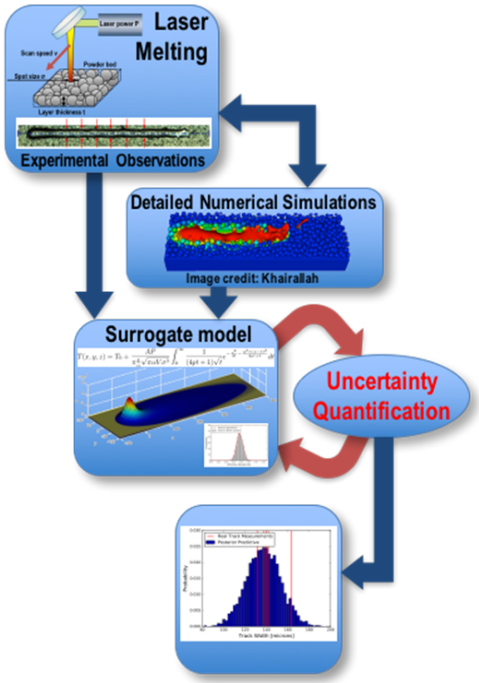


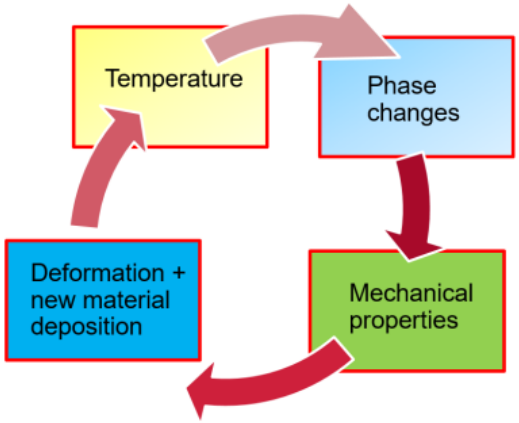
Image courtesy NASA/ARC



[UC Davis/UC Irvine]
Ref. LLNL-PRES-707401]

CALPHAD-Enhanced Model for Residual Stress

- Various possible levels of integration
- First level: Using CALPHAD properties in FEM (*present work*)
- Second: Post-processing FEM thermal histories with CALPHAD (*in progress*)
- Third: Querying CALPHAD at each FEM iteration (*under discussion*)



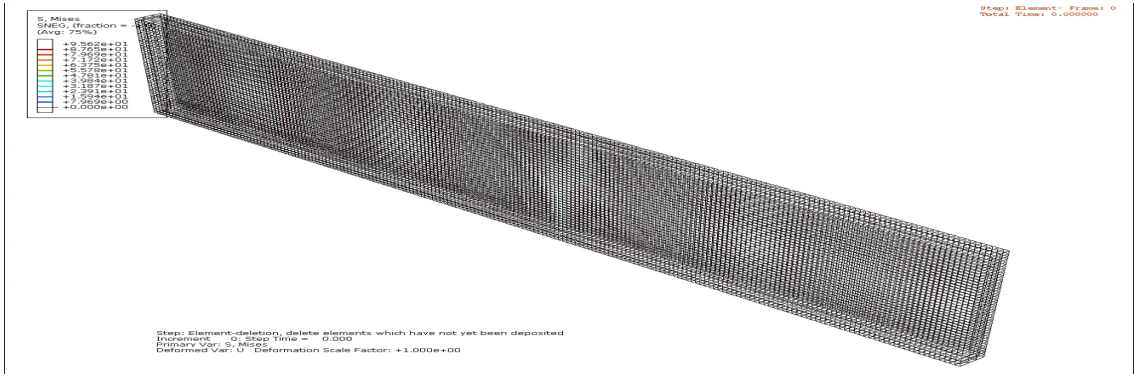
Coupled Thermomechanical Scheme

Why Couple CALPHAD to FEM

- 316L is a well-studied alloy system; why complicate the model with CALPHAD?
- We eventually want to consider
  - Non-traditional alloy systems and composites
  - Compositional gradients
  - Compositional sensitivity of results (UQ)
- The goal is to build our confidence using “known” cases

Setup for FEM Discrete State Model

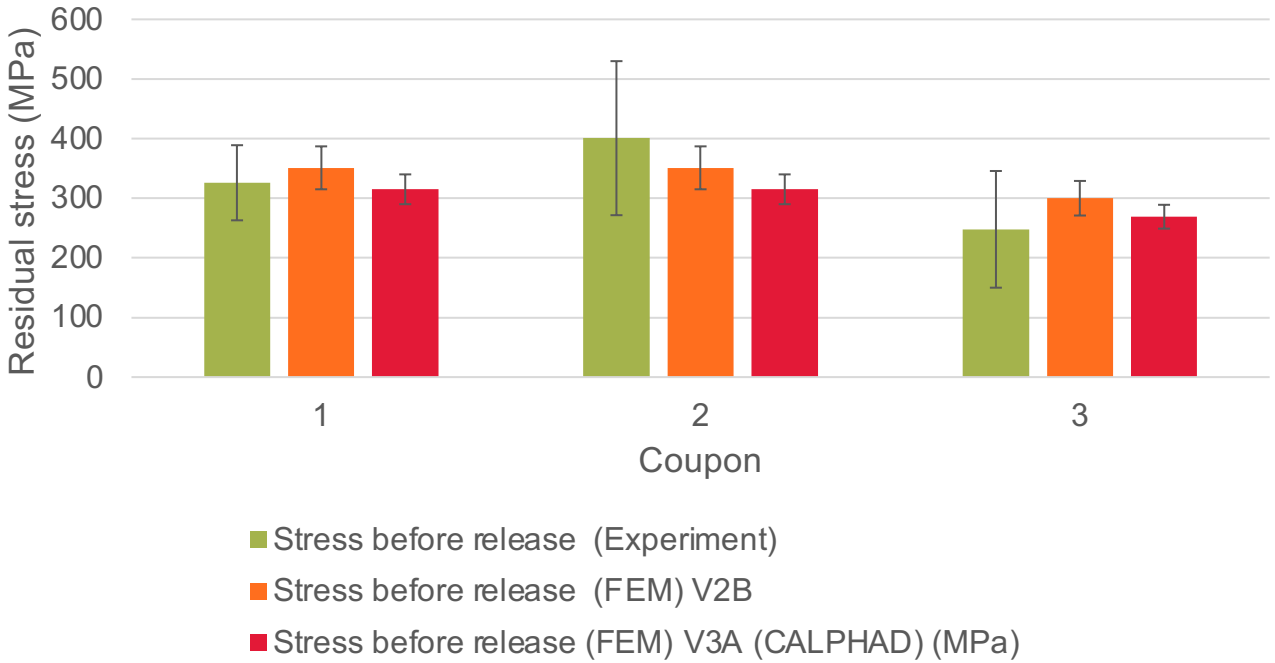
- 3D heat diffusion
- Three states considered
  - Unmelted powder
  - Liquid
  - Consolidated powder
- From CALPHAD
  - Transformation temperatures
  - Enthalpies of transformation
  - Heat capacities
  - Molar volumes
- Heat transport properties from commercial property library



Limitations of Approach

- Compositional heterogeneities not considered
- Many phenomena neglected, including
  - Secondary phase precipitation
  - Solid-state transformation strains
  - Microstructural effects, e.g., texturing

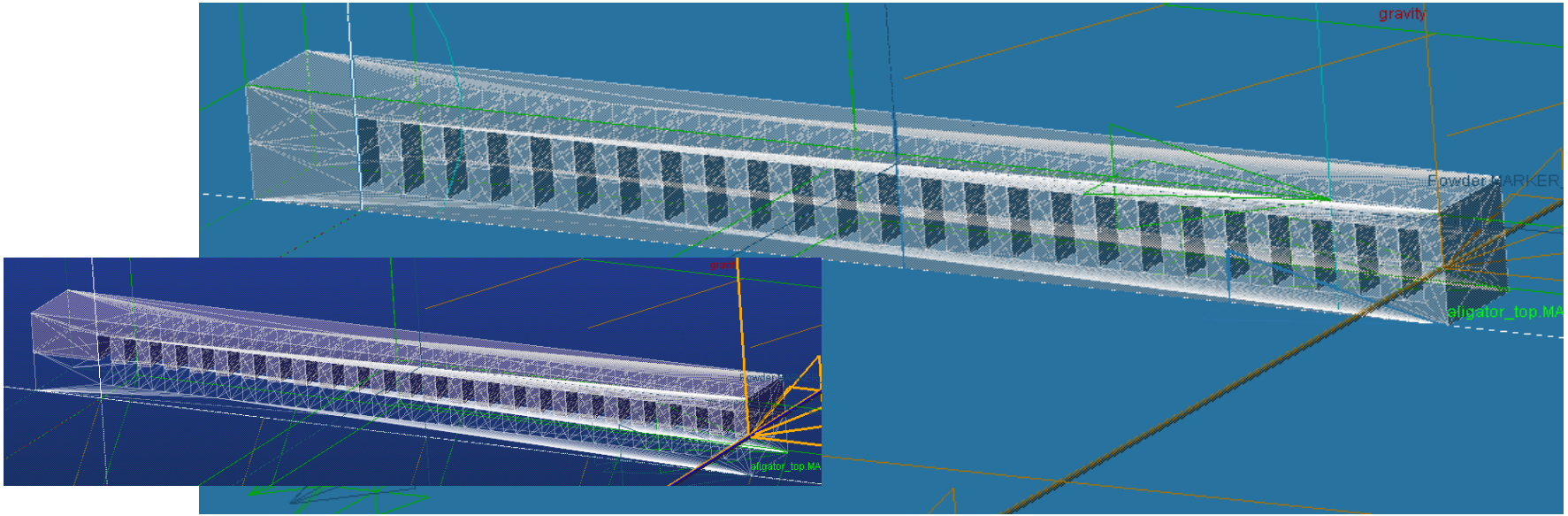
Results



- Models are consistent, but measurements are noisy

Experimental data by XRD, courtesy UC Irvine

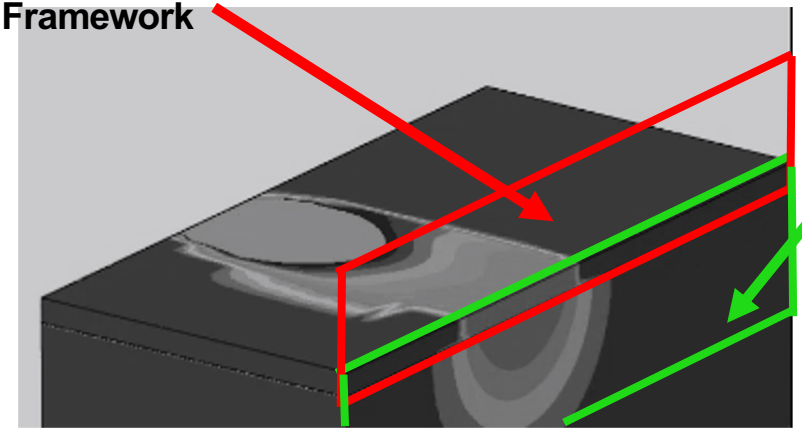
Part Level Build – Model Parallel Framework Rendering



- High fidelity FEM blocks (5 Build layers) result in part level design
- FEM Blocks include surrogate models using state bins (CALPHAD)
- High fidelity FEM blocks communicate in the framework via a modified volume based approach
- Coupled build of FEM building blocks in laser scan pattern (Part Level)

FEM Block LAYER Build – Heat Source Rendering – Heat transfer neighboring Block

- **5 Layer FEM Block m in Parallel Framework**

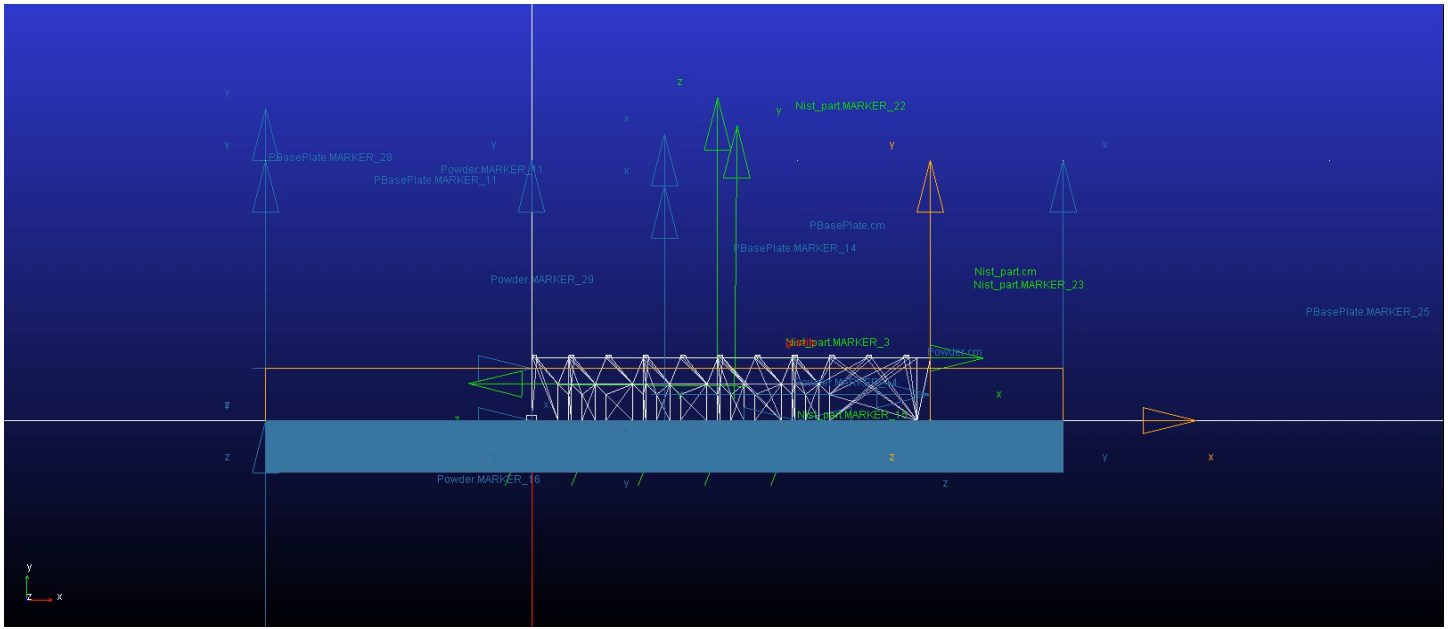


- **5 Layer FEM Block n in Parallel Framework**

Transient temperature with melt pool visualization

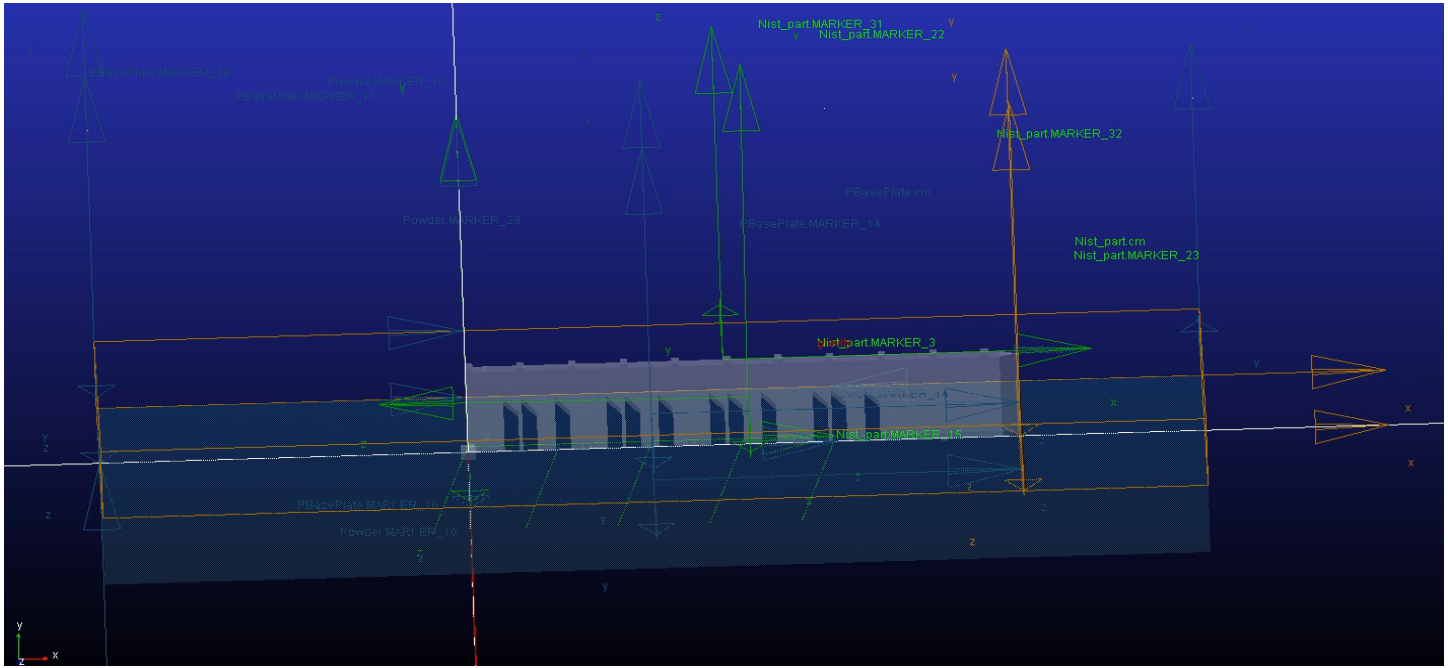
- Modified volume based equivalent load for part level thermomechanical model.
- Modified state of art fast approach
- Modification: Full solver method and high fidelity model of 5 layer blocks; not used for layer to layer as in non-modified method; 5 layer block, 1 layer overlay

EDM Wire Cut release – NIST Part – Aluminum – Parallel Framework



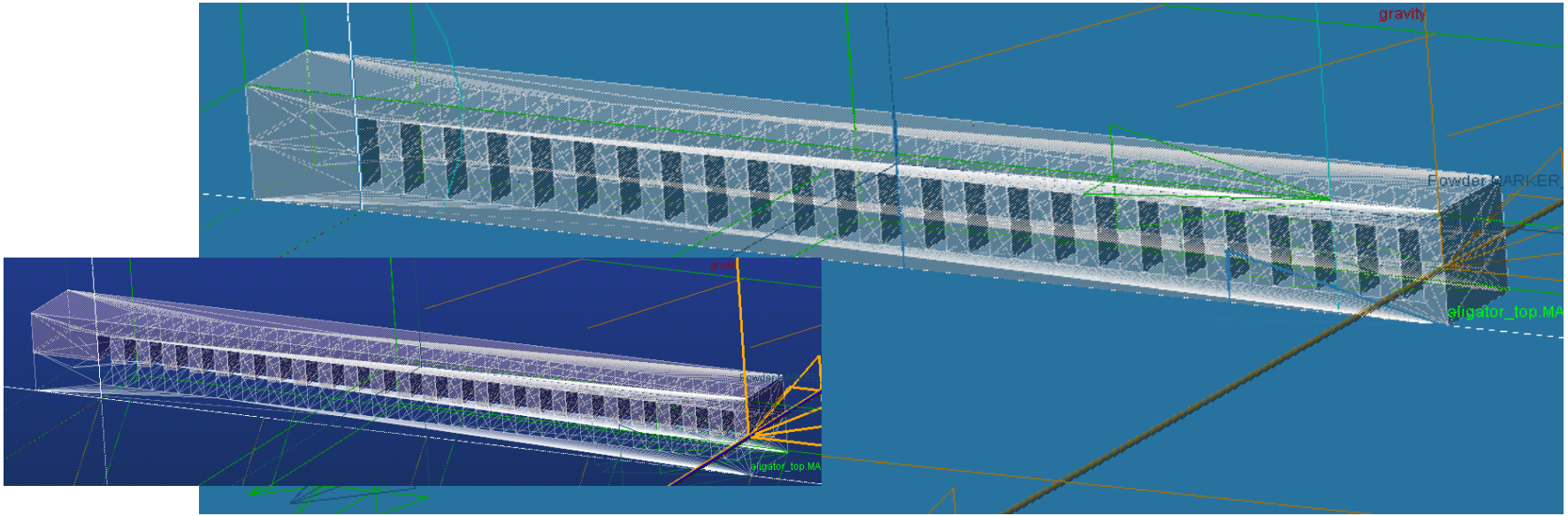
Markers on surfaces measure relative deformation after release

EDM Wire Cut release – NIST Part – Aluminum – Parallel Framework



Markers on surfaces measure relative deformation after release

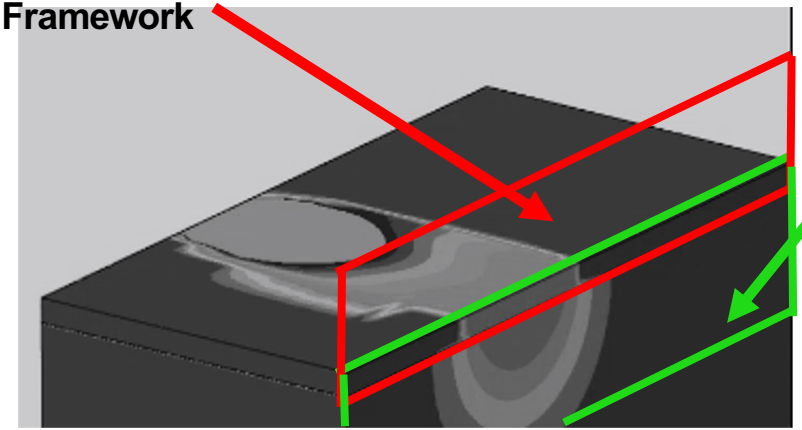
Part Level Build – Model Parallel Framework Rendering



- High fidelity FEM blocks (5 Build layers) result in part level design
- FEM Blocks include surrogate models using state bins (CALPHAD)
- High fidelity FEM blocks communicate in the framework via a modified volume based approach
- Coupled build of FEM building blocks in laser scan pattern (Part Level)

FEM Block LAYER Build – Heat Source Rendering – Heat transfer neighboring Block

- **5 Layer FEM Block m in Parallel Framework**



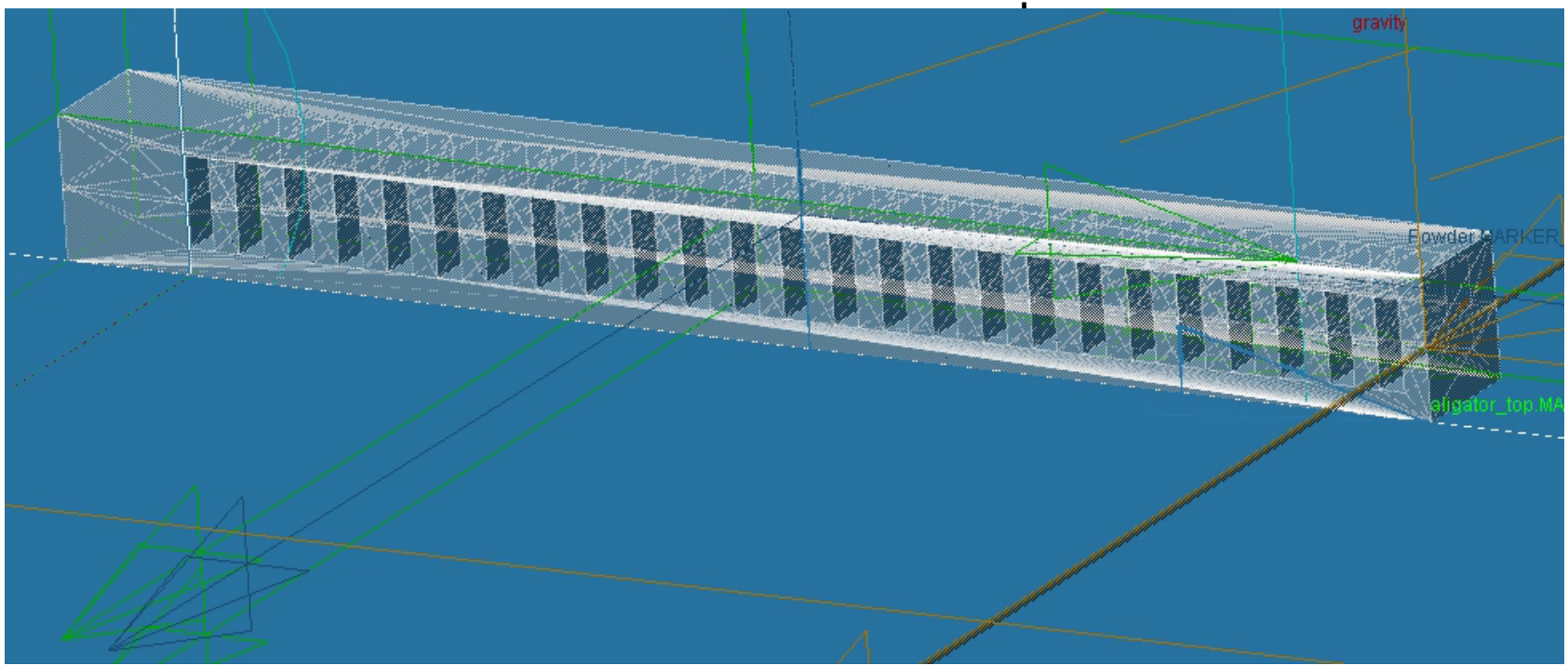
- **5 Layer FEM Block n in Parallel Framework**

Transient temperature with melt pool visualization

- Modified volume based equivalent load for part level thermomechanical model.
- Modified state of art fast approach
- Modification: Full solver method and high fidelity model of 5 layer blocks; not used for layer to layer as in non-modified method; 5 layer block, 1 layer overlay

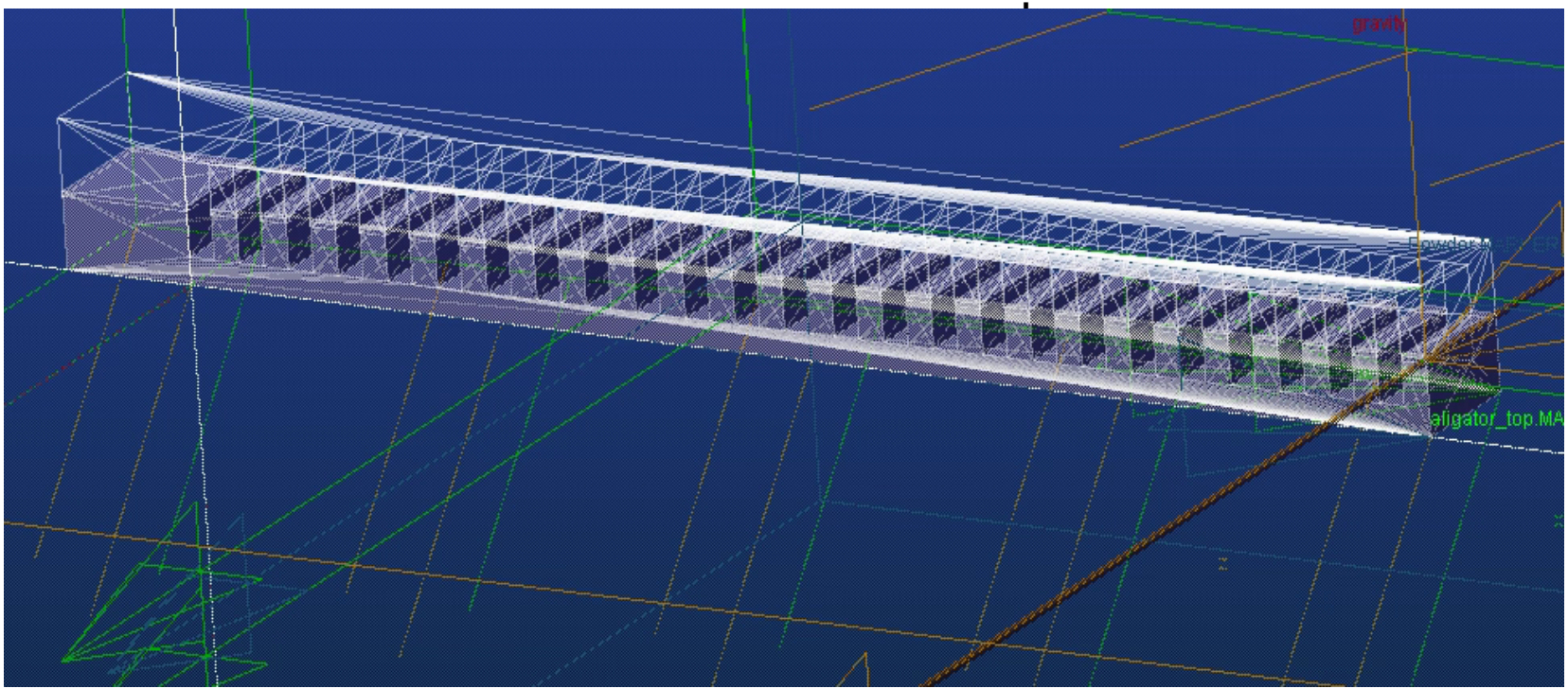
Residual Stress Release – Parallel Framework Visualization

Top



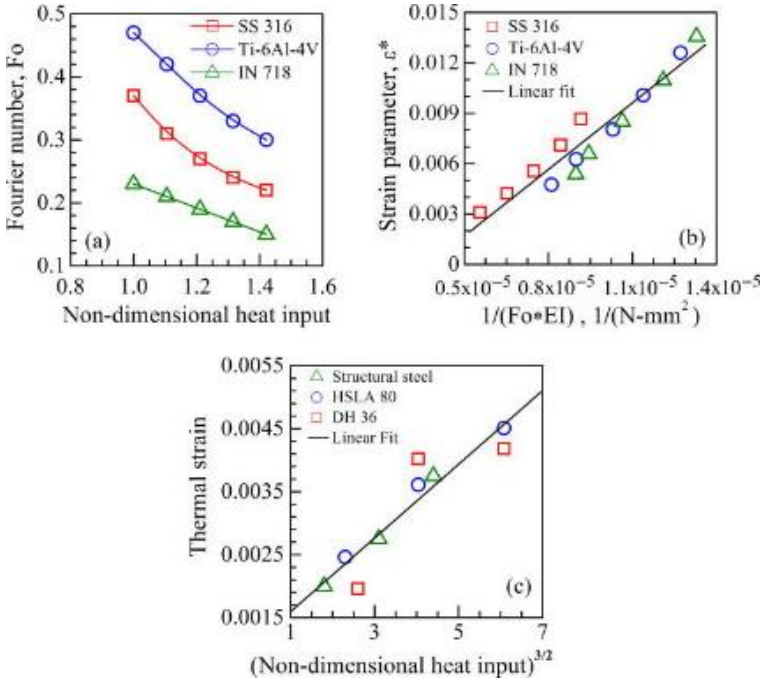
Residual Stress Release – Parallel Framework Visualization

Bottom



Next Steps

- Model sensitivity analysis
  - “Would further CALPHAD integration help?”
- Calculation of transformation-induced stresses
- Surrogate models, toward part-level simulation and UQ
  - Dimensionless numbers as a guide?



T. Mukherjee; V. Manvatkar; A. De; T. DebRoy; *Journal of Applied Physics*, 2017, 121

Jet Propulsion Laboratory
California Institute of Technology